Rec'd PCT/PTO 26 MAR 2002
10/088976

A THERMAL SENSOR CIRCUIT

FIELD OF THE INVENTION

The present invention relates to thermal sensor circuits. In particular, the invention relates to thermal sensor circuits for sensing temperature-related characteristics of a semiconductor device.

BACKGROUND OF THE INVENTION

Integrated circuits (ICs) are generally manufactured on semiconductor substrates (also called wafers) by a process involving deposition. Other semiconductor materials are thermally driven into the substrate. Because of the small size of the ICs, numerous ICs are fabricated using a single dye on the same wafer. The ICs are then separated by cutting. Due to unpredictable variations in the manufacturing process from dye to dye, as well as from wafer to wafer, the characteristics of the individual ICs are not identical. By measuring the characteristics of the manufactured ICs, these variations can be found.

In order to sense the temperature of the IC, a thermal sensor circuit is formed on the chip carrying the IC. If the variations in the temperature sensing characteristics of the sensor circuit are not within an acceptable range, the IC must be discarded as being defective, resulting in a lower IC manufacturing yield. It is therefore desirable to provide compensation for the manufacturing process variations so that the ICs need not be discarded.

The circuit components of the thermal sensor circuit on each IC chip will generally be sufficiently proximate to each other that they will all be affected by the process variations to a similar extent.

An example of a conventional temperature sensor circuit is shown in Figure 1. The temperature is sensed by comparing the linearly varying voltage at V_{sense} with the (ideally) fixed reference voltage V_{ref}. For example, if V_{sense} is 0 volts at 20 degrees Celsius and 1 volt

at 120 degrees, for every 10 degrees V_{sense} increases by 0.1 volts. If it is desired to detect when the temperature reaches 100 degrees, V_{ref} should be set to 0.8 volts. When V_{sense} is less than 0.8 volts, the temperature will be below 100 degrees and the comparator output will be low. When V_{sense} is greater than 0.8 volts, the temperature will be greater 100 degrees and the comparator output will be high. In order to accurately sense whether the temperature of the IC has passed a particular threshold temperature, V_{ref} must not vary with temperature. Otherwise this will give a spurious result as to the sensed voltage at the output of the comparator. However, due to IC manufacturing process variations, V_{ref} will sometimes vary with temperature.

In order for all the manufactured ICs to meet the required parameters, the process variations need to be taken into account during the design stage of the ICs. The circuits sensitivity to these process parameters must be minimized to get minimal difference in the performance of the circuit from IC to IC.

Transistors Q1 and Q2 are used to generate a voltage across the resistor R1 which is independent of any process variation. This voltage is effectively a property of the Silicon of the transistors and is therefore accurately reproducible. The voltage across the resistor R1 is given by the difference of the base-emitter potentials of transistors Q1 and Q2,

$$V_{be1} - V_{be2} = k \cdot T \cdot \ln(M)$$

where k is Boltzmann's constant, T is absolute temperature and M is the ratio (M:1, for M > 1) of the emitter areas of Q2 to Q1. The temperature sense voltage V_{sense} is measured over the temperature sensing resistor R3 and is given by,

$$V_{sense} = \frac{R3}{R1} \cdot k \cdot T \cdot \ln(M)$$

It is clear from the equation above that the V_{sense} is not affected by variations in the process.

since the process dependent components in the equation, resistors R3 and R1, appear as a ratio and will generally be affected by the process variations to the same extent. The "current mirror 1" circuit shown in Figure 1 is modelled as an ideal p-n-p current mirror for simplicity of explanation.

A reference "bandgap" voltage is obtained at the base of Q1 and Q2, such that the value is almost constant over temperature and is given by,

$$V_{ref} = V_{be1} + \frac{R2}{R1} \cdot k \cdot T \cdot \ln(M)$$

As the temperature varying term of the above equation is small relative to the base-emitter voltage of transistor Q1, V_{ref} changes as V_{be1} changes due to process variations.

Figure 3a illustrates the relationships of V_{sense} and V_{ref} over varying voltage and temperature. As can be seen from the plot of Figure 3a, the normal level of Vref will be crossed by the linearly varying Vsense measurement at the desired temperature level, T0. When the process variations have resulted in changed characteristics of the sensing circuit, this will have the effect of changing the level of Vref so that, for characteristics corresponding to the 'process minimum', Vref will be higher and will be crossed by Vsense at a higher temperature, T2, and for characteristics corresponding to the 'process maximum', Vref will be lower and will be crossed by Vsense at a lower temperature, T1. Temperatures T1 and T2 are spurious results, which, if the temperature differential between these two values is large, can cause an unacceptably high number of occurrences of spurious high temperature alert signals for the IC.

Figure 3b shows the output of the comparator corresponding to the spurious temperature detections at temperatures T1 and T2 as shown in Figure 3a.

It is therefore desirable to reduce the temperature difference (ie. T2 - T1) over which spurious detections occur for thermal sensing circuits in order to reduce the number of occurrences of

spurious high temperature alert signals for the IC.

SUMMARY OF THE INVENTION

The present invention provides a thermal sensor circuit for sensing the temperature of an integrated circuit chip, the thermal sensor circuit including:

an output comparator for comparing a reference voltage, V_{ref}, with a sensed voltage, V_{sense}, the sensed voltage being measured from a sensing device;

a first circuit to which a reference voltage line is connected to measure V_{ref};

a first current mirror providing a first current input to the first circuit and to a compensation circuit;

a second current mirror providing a second current input to the compensation circuit and to the sensing device; and wherein

the compensation circuit provides a current gain, defined as the ratio of the second current input to the first current input, for compensating for variations in V_{ref} due to variations of the characteristics of the thermal sensing circuit arising from manufacture by adjusting the second current input in dependence on the variations of the characteristics to thereby vary V_{sense} with V_{ref}.

Preferably, the compensation circuit includes first, second, third and fourth bipolar junction transistors (BJTs) wherein:

the first BJT has a collector terminal connected to the first current input of the first current mirror, a base terminal connected to a common base connection and an emitter terminal connected to ground;

the second BJT has a collector terminal connected to the second current input of the second current mirror, a base terminal connected to the common base connection and an emitter terminal connected to ground;

the third BJT has a collector terminal connected to the second current input, a base terminal connected the first current input and an emitter connected to the common base connection;

the fourth BJT has a collector terminal connected to a voltage supply of the thermal

sensor circuit, a base terminal connected to the common base connection and an emitter terminal connected to ground; and

the ratio of emitter area of the fourth BJT to the emitter areas of the first, second and third BJTs is N : 1, where N >0.

Preferably, the first circuit includes fifth and sixth BJTs, wherein:

the fifth BJT has a collector terminal connected to the first current input, a base terminal connected to the reference voltage line and an emitter terminal connected to an output point of the first circuit via a first resistor;

the sixth BJT has a collector terminal connected to the first current input, a base terminal connected to the reference voltage line and an emitter connected to the output point of the first circuit;

the output point of the first circuit is connected to ground via a second resistor.

Preferably, the ratio of emitter area of the fifth BJT to the emitter area of the sixth BJT is M:1, where M >1. Preferably, each of the first to sixth BJTs is an n-p-n transistor.

Preferably, the current gain is given by:

$$\frac{I2}{I1} = \frac{\beta^2 + (3+N)\beta}{\beta^2 + \beta + (2+N)}$$

where:

$I1$ is the first current input;

$I2$ is the second current input; and

β is the common-emitter current gain of each of the first to sixth BJTs.

Preferably, the first and second current mirrors are connected to the voltage supply of the thermal sensor circuit and use p-n-p BJTs to supply the first and second current inputs, respectively.

Advantageously, the thermal sensor circuit provides a compensation function which reduces

the temperature range over which spurious temperature detection signals are sent by the comparator by providing a compensation circuit which provides current gain to adjust V_{sense} according to the degree of process variations effected by the manufacturing process of the IC on the thermal sensing circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a circuit diagram of a known temperature sensing circuit;

Figure 2 is a circuit diagram of a known current mirror circuit;

Figure 3a is a graph of voltage versus temperature, showing the relationship between the sensed voltage and the reference voltage of the temperature sensing circuit of Figure 1;

Figure 3b is a plot of the output of the comparator of the temperature sensing circuit of Figure 1 corresponding to the graph of Figure 3a;

Figure 4 is a circuit diagram of a modified current mirror circuit employed in an embodiment of the invention;

Figure 5 is a circuit diagram of a temperature sensing circuit according to an embodiment of the invention;

Figure 6a is a graph of voltage versus temperature, showing the relationship between the sensed voltage and the reference voltage of the temperature sensing circuit of Figure 5;

Figure 6b is a plot of the output of the comparator of the temperature sensing circuit of Figure 5 corresponding to the graph of Figure 6a;

Figure 7 is a comparative plot of current gain versus process variation.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

A typical n-p-n current mirror circuit is shown in Figure 2, the current gain (I2/I1) of which is given by,

$$Gain = \frac{I2}{I1} = \frac{\beta^2 + \beta}{\beta^2 + \beta + 2}$$

where β is the common-emitter current gain of a BJT. Generally, a process minimum corresponds to a smaller β, and is called a process minimum because the circuits tend to operate more slowly. Similarly, a process maximum corresponds to a larger β, where the circuits tend to operate faster. For smaller values of β, the current gain is less than 1. As β increases, the gain approaches 1.

A compensation circuit 10 is shown in Figure 4, similar to that shown in Figure 2 except for a few important differences. Compensation circuit 10 includes an additional transistor Qd, the base terminal of which is connected to the common base connection of current mirror transistors Qa and Qb and the collector terminal of which is connected to the supply voltage, Vdd, of the thermal sensor circuit. The emitter terminal of Qd is connected to ground 14, in common with the emitter terminals of Qa and Qb. The emitter area of Qd is larger than the emitter areas of Qa, Qb and Qc by a ratio of N:1, where N≥0. N will usually be equal to or larger than 1 but may effectively be zero by providing an open circuit in place of Qd. Also in contrast to Figure 2, instead of the collector of transistor Qc being connected to the supply voltage Vdd, it is connected in parallel with the collector of Qb. The gain of the compensation circuit of Figure 4 is given by:

$$\frac{I2}{I1} = \frac{\beta^2 + (3 + N)\beta}{\beta^2 + \beta + (2 + N)}$$

Figure 5 shows the compensation circuit 10 of Figure 4 in use in a thermal sensing circuit 2.

The compensation circuit 10 is placed in combination with first and second current mirrors 6, 7, a bandgap reference circuit 8 and a comparator 4. The bandgap reference circuit 8 and the comparator 4 operate in a similar manner to that of the thermal sensor circuit of Figure 1. Transistors Q1, Q2 of the reference circuit and Qa, Qb, Qc and Qd of the compensation circuit are all n-p-n transistors having similar characteristics (apart from the larger emitter areas of Q2 and Qd).

The relative sizes of resistors R1, R2 and R3 serve to define the levels of V_{ref} and V_{sense} and will be set according to the threshold temperature which it is desired to detect the passing of. Typically, R2 and R3 are of similar values while R1 is relatively much smaller.

The reference current I1 from the first current mirror 6 is given a current gain by the compensation circuit 10 to draw a compensated output current I2 from current mirror 7. The current I2 drawn through the compensation circuit must, by the nature of an ideal current mirror, be reflected through the other current supply line of the current mirror 7 which runs through thermal sensing resistor R3 to give a potential difference over R3 corresponding to V_{sense}. Thus, the compensation circuit 10 provides a current gain of I2 with respect to I1. The current gain provided (I2/I1) is more than the typical value when the process is minimum and less than the typical gain when the process is maximum.

Some sample gain values are calculated below:

Process minimum $\Rightarrow$ small β; increased V_{ref}.
Process mean $\Rightarrow$ typical β; normal V_{ref}.
Process maximum $\Rightarrow$ larger β; decreased V_{ref}.

For the typical current mirror:
Small $\beta = 5$; $I2/I1 = 0.938 < 1$;
Typical $\beta = 20$; $I2/I1 = 0.995$.
Larger $\beta = 50$; $I2/I1 = 0.999 \approx 1$.

For the compensation circuit, with N=1:
Small β = 5; I2/I1 = 1.364> 1;
Typical β = 20; I2/I1 = 1.135.
Larger β = 50; I2/I1 = 1.058 ≈ 1.

The thermal sensor circuit 2 having the compensation circuit 10 therefore provides compensation for the process variations by providing a current gain to adjust the sensed voltage, V_{sense}, over thermal sensing resistor R3. The compensated V_{sense} is given by:

$$V_{sense\,(compensated)} = \frac{\beta^2+(3+N)\beta}{\beta^2+\beta+(2+N)} \cdot \frac{R3}{R1} \cdot k \cdot T \cdot \ln(M)$$

In an alternative embodiment of the invention, the current mirrors 6 and 7 may be implemented with n-p-n transistors and the reference and compensation circuits may be implemented with p-n-p transistors. This would necessitate a reversal of polarity for the terminals of the comparator 4 and would require changing the relative roles of the voltage supply and ground lines.

Figure 6a shows a plot (which is not to scale) of V_{ref} and V_{sense} versus temperature for the compensated thermal sensor circuit 2. It can be seen that V_{sense} is increased for process minimum scenarios and is decreased for process maximum scenarios. This compensation of V_{sense}. reduces the temperature range over which spurious temperature measurements are recorded, leading to greater accuracy of the thermal sensor circuit, fewer ICs being discarded because of irredeemable process variations and a correspondingly higher IC manufacturing yield. Figure 6b shows the output of the comparator 4 corresponding to reduced band of spurious temperature detections at temperatures T1 and T2 as shown in Figure 6a.

Advantageously, by appropriately choosing the area of Qd, the current gain of the compensation circuit can be modified to effectively provide a 'DC shift' to the measured V_{sense} in order to track the variations in Vref due to process variations, thereby enabling an accurate sensing of the temperature independent of the process variations. The amount of variation in the current gain, and hence compensation of Vsense, can be adjusted by changing the emitter

area N of transistor Qd to suit a particular batch of IC chips.

Figure 7 shows the relationship between the current gain and the process variations for both the proposed compensation circuit (for N=0, 1 and 2) and an exemplary "typical mirror" circuit employed in place of the compensation circuit in Figure 5. The use of the "typical mirror" in place of the compensation circuit in Figure 5 is not believed to form part of the prior art but is used here for the purposes of comparison.